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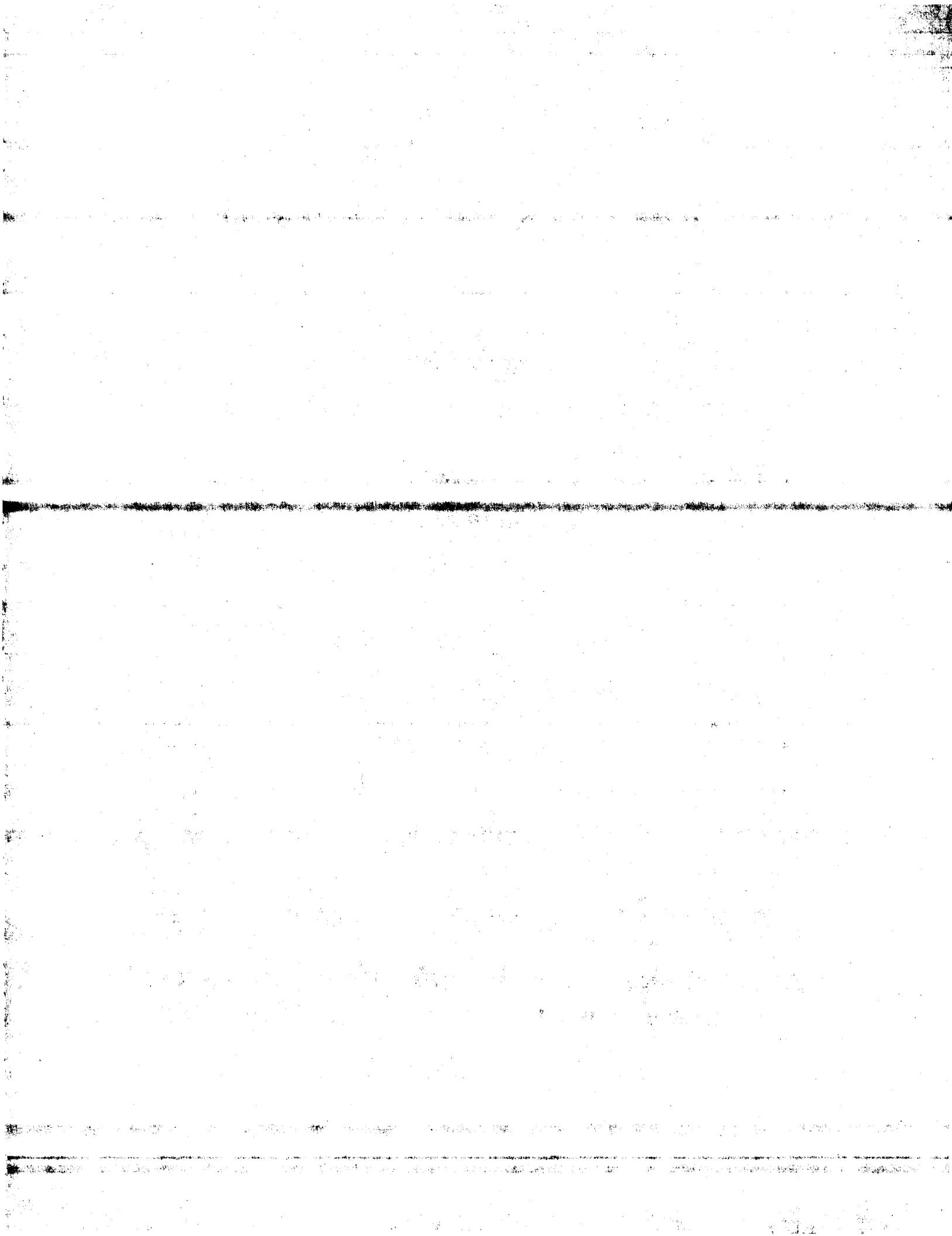
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# PCT

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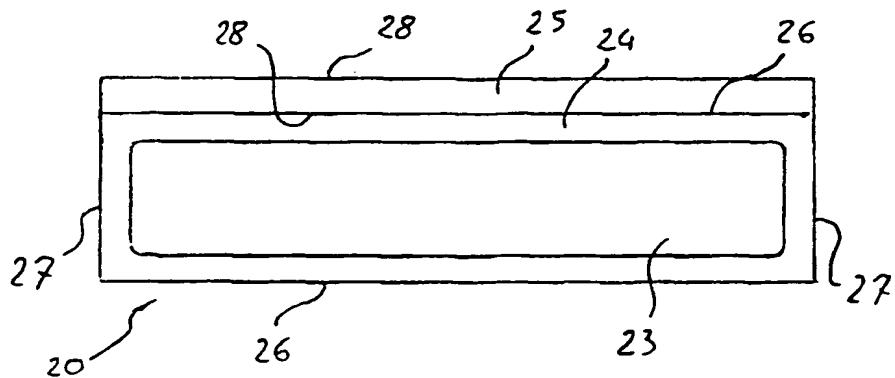
## INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification <sup>6</sup> :	A1	(11) International Publication Number:	<b>WO 99/08289</b>
H01B 12/02		(43) International Publication Date:	18 February 1999 (18.02.99)
(21) International Application Number:	PCT/EP98/04991	(81) Designated States:	AU, BR, CA, CN, JP, KR, NZ, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).
(22) International Filing Date:	28 July 1998 (28.07.98)		
(30) Priority Data:	97202433.5 5 August 1997 (05.08.97) EP 60/059,986 25 September 1997 (25.09.97) US	Published	<i>With international search report. Before the expiration of the time limit for amending the claims and to be republished in the event of the receipt of amendments.</i>
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(54) Title: HIGH TEMPERATURE SUPERCONDUCTING CABLE AND PROCESS FOR MANUFACTURING THE SAME

### (57) Abstract

A high temperature superconducting cable comprises a tubular support, a plurality of superconducting tapes spirally wound onto said support so as to form one or more superconducting layers, electroinsulating means for the superconducting layer, refrigerating means and thermal insulation means to keep the superconducting layer below a predetermined working temperature. According to the invention, the superconducting tapes comprise superconducting material enclosed by a metal covering to which at least a metal strip is connected.



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High temperature superconducting cable and process for  
manufacturing the same

DESCRIPTION

The present invention relates to a superconducting cable of  
5 the so-called high temperature type, and a manufacturing  
process for the same.

The term superconducting material, as employed throughout  
the description and the appended claims, refers to any  
material, such as for instance ceramic materials based on  
10 mixed oxides of copper, barium and yttrium or of bismuth,  
lead, strontium, calcium, copper, thallium and mercury,  
comprising a superconducting stage having an almost null  
resistivity at temperatures below a so-called critical  
temperature  $T_c$ .

15 In the field of superconductors and, accordingly, in the  
present description, the term high temperature refers to  
any temperature near to or higher than the temperature of  
liquid nitrogen (about  $77^\circ\text{K}$ ), compared to the temperature  
of liquid helium (about  $4^\circ\text{K}$ ), usually indicated as low  
20 temperature.

High temperature superconducting cables are known for  
instance from DE-A-3811050 and EP-A-0747975.

Superconducting materials are known that have a critical  
temperature higher than  $77^\circ\text{K}$ , i.e. that show  
25 superconductivity characteristics at least up to such  
temperature. These materials are usually referred to as  
high temperature superconductors. Such materials are  
obviously of a greater technical interest with respect to  
low temperature superconductors, as their working may be  
30 ensured by liquid nitrogen refrigeration at  $77^\circ\text{K}$  instead of  
liquid helium at  $4^\circ\text{K}$ , with much lower implementation  
difficulties and energy costs.

As known, in the field of electric energy transportation,

one of the problems of most difficult solution is that of rendering more and more advantageous the use of the so-called superconducting materials, from both the technological and the economic points of view.

- 5 In fact, even though these low temperature materials have been known for a long time, their diffusion was limited till now to some well defined practical applications, such as for instance the fabrication of magnets for NMR apparatuses or high field magnets for which cost is not a  
10 discriminating factor.

Actually, cost savings due to less power being dissipated by superconductors is still more than counterweighted by costs due to liquid helium refrigeration, necessary to keep the latter below its critical temperature.

- 15 In order to solve the aforesaid problem, research is partly oriented towards experimenting new high temperature superconducting materials, partly tries to constantly improve both the characteristics of the existing materials and the performances of conductors incorporating already  
20 available materials.

With regard to geometric characteristics, it has been found that an advantageous geometry is provided by thin tapes having generally a thickness of between 0,05 and 1 mm.

- In fact, in such case the conductor comprising the very  
25 brittle superconducting ceramic material achieves on one hand an improved resistance to various bending stresses to which it is submitted during each manufacturing, shipping and installing operations of the cable containing it, and on the other hand it provides better performances with  
30 regard to critical current density, because of the more advantageous orientation and compacting degree of the superconducting material.

For various reasons and in particular to improve mechanical resistance, the above conductors generally comprise a

plurality of tapes, formed each by a core of superconducting material enclosed in a metal envelope - generally of silver or silver alloys - coupled together to obtain a multi-filament composite structure.

- 5 According to a widely used method, known to those skilled in the art as "powder-in-tube", this multi-filament structure of the conductor is obtained starting from small metal tubes filled with a suitable powder precursor, said tubes being in their turn enclosed in another external  
10 metal tube or a billet, so as to obtain a compact bundle of tubes which are submitted first to several subsequent permanent deformation, extrusion and/or drawing treatments, then to rolling mill and/or pressing treatments, until the desired tape-shaped structure is obtained. See for  
15 instance EP-A-0627773.

Between a rolling mill treatment and the subsequent one, the tape being worked is submitted to one or more heat treatments to cause formation of the superconducting ceramic material starting from its precursor and, above  
20 all, its syntherisation, i.e. the mutual "welding" of the granules of the powdered superconductor.

The tapes of high temperature superconductors are rather brittle, both at the working temperature of 77°K and at room temperature, and are unsuited to stand mechanical  
25 stresses, especially tensile stresses. In fact, apart from an actual mechanical breaking, exceeding a given tensile deformation threshold irreversibly jeopardises the superconducting characteristics of the material. Therefore, using these materials in cables is particularly  
30 complex and delicate.

In fact, the manufacturing and installation of cables comprising such materials involves several stages which bring about unavoidably mechanical stresses.

A first critical stage is winding of several tapes on a

flexible tubular support according to a spiral arrangement, until the desired section of superconducting material is obtained. Both winding and pull cause tensile, bending and torsion deformations in tapes. The resulting stress  
5 applied to the superconducting material is mainly a tensile stress. Besides, the so formed conductor (support plus superconducting material) is surrounded by heat and electric insulation means, and is submitted, during these operations, to tractions and bendings that introduce more  
10 stresses in superconducting tapes.

A second critical stage concerns cable installation. The cable is indeed installed at room temperature, so as to cause additional tensile and bending stresses, and mechanical connections (locking of cable heads), electric  
15 and hydraulic connections (for liquid nitrogen) are carried out at room temperature. After completing installatio, the cable is brought to its working temperature by feeding liquid nitrogen, and during such cooling each cable component is subject to mechanical stresses of thermal  
20 origin, different according to the thermal expansion coefficient of the constituiting material and of the characteristics of the other elements.

In particular, the differences of expansion coefficients between the support and the superconducting tape may cause  
25 stresses in the latter and therefore in the superconducting material. In fact, if the superconducting material cannot shrink freely being tied to a less shrinkable support, tensile strains generate in the superconducting material. Such tensile strains add to those already present, due to  
30 winding.

To reduce tensile strains, use of supports has been suggested that are made of a material having an expansion coefficient higher than that of the superconducting material (usually equal to  $10 \div 20 \text{ } 10^{-6}/\text{K}$ ), i.e. in the  
35 order of at least  $75 \text{ } 10^{-6}/\text{K}$ . Such material would not be a metal, as no metal has such values, but only a polymeric

material, such as for instance teflon®, polyethylene, and derivatives thereof.

However, it has been found that the aforesaid solution, whose aim is to reduce thermomechanical stresses on tapes 5 through a suitable reduction in the support diameter, shows some important drawbacks.

In particular, the unavoidably high values of heat contraction of the conductor (support plus superconducting material) cause the formation of a wide radial hollow space 10 between the conductor itself and the surrounding insulating means (thermal and/or electric insulation). This hollow space may cause electric inconveniences, with deformation or breaking of the insulation, and/or mechanical inconveniences, namely lack of cohesion, misalignment, and 15 slipping of the conductor.

Besides, poor mechanical characteristics of said polymer material do not allow to protect the superconducting material adequately during cable manufacturing and installation phases: because of the high deformability of 20 these materials any strain applied to conductors causes indeed a remarkable deformation also in the superconducting material.

Therefore, the invention relates, in a first aspect, to a high temperature superconducting cable, comprising a 25 tubular support, a plurality of superconducting tapes including a superconducting material enveloped in a metal covering (for instance, silver or a silver-based alloy with magnesium and/or aluminium and/or nickel), said tapes being spirally wound on the support, so as to form an 30 electroinsulated, thermally-insulated and refrigerated superconducting layer, characterised in that the superconducting tapes have a maximum tensile deformation greater than 3%.

The above value is to be intended as referred to the

manufacturing and installation process described above, i.e.: winding and installation at room temperature, then cooling to working temperature of about 77°K. The same applies also to the deformation values that will be given  
5 in the following.

Preferably, the superconductive tapes comprise at least a metal strip (or band or laminate) connected to the metal covering.

In this way, the capability of bearing tensile stresses  
10 increases. It has been observed that tensile deformation safely bearable by superconducting materials may be - at the best - of about 3%; this figure takes into account the fact that the superconducting materials already bear a compression deformation of about 1 ÷ 1,5%, because of  
15 different thermal contraction of the superconducting material with respect to the metal covering during the tape fabrication stage.

Thanks to the metal strip of the invention, not only a lower deformation under the same applied strains has been  
20 observed, but especially an improved tensile deformation resistance; elongation values equal to about 5.5% have been actually reached without any damage. This effect is thought to be due to a more uniform distribution of strains in the superconducting material, that allows to better  
25 exploit the mechanical characteristics of said superconducting material.

According to each individual case, only one strip coupled to the metal covering, or two strips, located at the opposite sides of the tape, can be provided.

30 Preferably, the metal strip is coupled to the metal covering by welding, brazing or gluing.

Preferably, the strip is made of non magnetic stainless steel having a low electric conductivity, or also of bronze or aluminium.

Preferably, the tubular support of the cable is made of metal. The greater capability of bearing tensile stresses allows indeed to use a support made of metal instead of polymeric material, as will be better explained in the  
5 following.

Various types of metals may be used for the support; in particular, for applications with very high currents, non-magnetic steel is used, preferably stainless steel. Alternatively, copper or aluminium may also be used.

- 10 The structure of the tubular support may be continuous, either smooth or corrugated. Alternatively, the tubular support may have a structure formed by a spirally wound metal tape, or may have a so-called tile-structure, i.e. with spirally connected adjacent sectors.
- 15 In a second aspect, the invention relates to a process for manufacturing high temperature superconducting cables, comprising the steps of:
  - providing a tubular support,
  - enclosing a superconductive material in a metal covering, so as to form superconductive tapes,
  - 20 - spirally winding a plurality of superconducting tapes onto the support so as to form at least a superconducting layer,
  - electroinsulating the superconductive layer,
  - 25 - thermally insulating the superconductive layer,
  - providing the possibility of refrigerating the superconductive layer below a predetermined working temperature, when cables are in use,  
**characterised by**
- 30 - controlling the maximum tensile deformation of the superconducting tapes to have it greater than 3%.

This process allows to manufacture cables according to the first aspect of the invention.

Further characteristics and advantages of a cable and a

process according to the invention will appear more clearly from the following description of a preferred embodiment, wherein reference is made to the attached drawings. In said drawings:

- 5 Figure 1 is a schematic view of a high temperature superconducting cable according to the invention, with partly removed parts.

Figure 2 is a cross-section schematic view of a high

temperature superconducting tape utilised in the cable of

- 10 Figure 1.

With reference to Figure 1, 1 indicates a one-phase superconducting cable 1 of the so-called co-axial type as a whole. Cable 1 comprises a superconducting core, globally indicated by 2, comprising at least a conducting element 3;

- 15 the illustrated example relates (according to the European patent application no. 96203551.5 of the same applicant) to a cable wherein four conducting elements are provided, indicated by 3<sup>I</sup>, 3<sup>II</sup>, 3<sup>III</sup>, 3<sup>IV</sup>, housed - preferably loosely - within a tubular casing 9, for instance of metal, such as

20 steel, aluminium and the like.

Each of the conducting elements 3 comprises a couple of co-axial conductors, respectively of phase 4 and of neutral 5, including each at least a layer of superconducting material.

- 25 In said example, the superconducting material is incorporated in a plurality of superposed superconducting tapes 20, spirally wound on respective tubular supports 6 and (possibly) 7, with a sufficiently low winding angle  $\alpha$ ; if the tubular support is metal, the angle  $\alpha$  is preferably smaller than 40°, as will be illustrated in the following.

Co-axial phase 4 and neutral 5 conductors are electrically insulated from one another by means of an interposed layer 8 of dielectric material.

Cable 1 also comprises suitable means to refrigerate the superconducting core 3 to a temperature suitably lower than the critical temperature of the chosen superconducting material, which in the cable of Figure 1 is of the so-called "high temperature" type.

The aforesaid means comprise suitable, known and thus not represented, pumping means, whose purpose is feeding a suitable refrigerating fluid, for instance liquid nitrogen at a temperature of from 65° to 90°K, both in the interior 10 of each of the conducting elements 3, and in the interstices between such elements and the tubular casing 9.

To reduce as much as possible thermal dispersions toward environment, the superconducting core 2 is enclosed in a holding structure, or cryostat, 10 comprising a thermal 15 insulation formed, for instance, by a plurality of superposed layers, and at least a protection sheath.

A cryostat, known in the art, is described for instance in an article by IEEE TRANSACTIONS ON POWER DELIVERY, vol. 7, no. 4, October 1992, pp. 1745-1753.

20 More particularly, in said example, cryostat 10 comprises a layer 11 of insulating material, constituted for instance by several tapes (some dozens) from surface-metallised plastic material (for instance polyester resin), known in the art as "thermal superinsulator", loosely wound, 25 possibly with the aid of interposed spacers 13.

Such tapes are housed in an annular hollow space 12, delimited by a tubular element 14, in which vacuum of about  $10^{-2}$  N/m<sup>2</sup> is maintained by means of known apparatuses.

30 The metal tubular element 14 is suitable to give the annular hollow space 12 the desired impermeability, and is covered by an external sheath 15, for instance of polyethylene.

Preferably, the metal tubular element 14 is formed by a

tape wound in tubular shape and longitudinally welded, made of steel, copper, aluminium and the like, or by an extruded tube or the like.

If required for cable flexibility, element 14 may be  
5 corrugated.

In addition to the described elements, cable traction elements may also be present, axially or peripherally located based on the construction and use requirements of the same, to ensure limitation of mechanical stresses  
10 applied to superconducting elements 3; such traction elements, not shown, may be constituted, according to techniques known in the art, by peripherally placed metal armours, for instance by roped steel wires, or by one or more axial metal cords, or by armouring fibres of  
15 dielectric material, for instance aramid fibres.

Preferably, the tubular supports 6 and 7 are made of non magnetic stainless steel, and may have a continuous, either smooth or corrugated, structure; alternatively, tubular supports 6 and 7 may be realised with a spirally wound  
20 steel strip or with a tile structure. Materials different from steel may also be used, such as copper or aluminium.

Each superconducting tape 20, as shown in Figure 2, comprises superconducting material 23, a metal covering 24 (preferably from silver or silver alloy with magnesium,  
25 aluminium or nickel), wherein the superconducting material 23 is enclosed, and at least a metal strip (or band or laminate) 25 coupled to covering 24. In particular, covering 24 has a substantially rectangular flattened section with two long sides 26 and two short sides 27; also  
30 strip 25 has a substantially rectangular flattened section with two long sides 28 of a length almost equal to the long sides 26 of covering 24. Strip 25 is fastened to covering 24 by welding, brazing or gluing. It should be noted that there may be two strips 25, either equal or different,  
35 fastened to opposite parts of covering 24.

**EXAMPLE**

To put into practice the invention, some cables have been realised having the following characteristics:

support:

5 metal or polymer

winding diameter (external diameter of the support):

40 mm

angle  $\alpha$ :

10 - 45°

10 thickness of superconducting tape:

0.2 mm

width of superconducting tape:

4 mm

pull on individual tapes during winding:

15 10 N

working temperature:

77°K

refrigeration with locked heads (temperature jump equal to 220°K)

20 heat expansion coefficient of superconducting tape:

18,5  $10^{-6}$  °C

heat expansion coefficient of polymer support:

80  $10^{-6}$  °C

heat expansion coefficient of metal support:

15  $10^{-6}$  °C

The deformation effects on the superconducting material have been taken into account, both those due to winding geometry (which depend on bending imparted to the tape and  
5 which therefore increase as angle  $\alpha$  increases), and those due to pull during winding operation (constant), and those with locked cable heads due to the effect of thermal variation (which decrease as angle  $\alpha$  increases, until they may become negative with a sufficiently great  $\alpha$ ). In the  
10 tables, positive figures have been used to indicate pulling deformations, negative figures to indicate compression deformations.

The tables show the feasibility either by a conventional superconducting tape with a maximum bearable tensile  
15 deformation equal to 3%, and by a superconducting tape according to the invention (provided with two strips 25 located along sides 26 of the section, having a thickness of 0.045 mm and a length of 3,8 mm, made of stainless steel, bonded to covering 24 of the strip by tin brazing),  
20 with a maximum bearable tensile deformation equal to 5.5%, therefore with a 2.5% improvement. In the latter case, the minimum increase value of tensile deformation resistance necessary to ensure feasibility has been indicated, assuming (as indicated above and practically verified) that  
25 the superconducting non-reinforced tape can bear a 3% tensile deformation. Double-underlined values indicate that the 3% limit has been exceeded.

Table 1 summarises the situation in the case of a polymeric support, table 2 that relating to the case of a metal support.  
30

The example shows, in a specific case, that generally the invention allows a greater design freedom as concerns winding angles, support diameter, winding pull value, and, to some extent, choice of material for the support.

The possibility of using a metal for the support is particularly advantageous, as such support, besides imparting a greater solidity to the cable, therefore with a better protection for the superconducting material, above all allows to prevent those drawbacks of polymeric supports mentioned above for the prior art; this means that no dangerous hollow spaces form at the working temperature between the conductor and the surrounding layers, due to differences in heat expansion coefficient. Because in the cable the layers external with respect to the conductor are - as has been seen - prevailingly metal, using a metal support minimises expansion differences and therefore drastically reduces inconveniences due to hollow spaces.

Besides, the metal support lends a greater mechanical resistance to the conductor, understood as the whole of the support and the superconducting material wound on the same. Hence, possible mechanical stresses on the conductor are not transmitted to a great extent to superconducting tapes (as happens with polymer supports because of their high deformability), but are instead almost entirely borne by the same support.

Also the possibility of increasing the winding pull of the superconducting material is a very important advantage. In fact, compactness of the conductor winding, and therefore its stability, depends on said pull.

To sum up, the invention allows to realise less delicate and more resistant superconducting cables.

Table 1 - Polymer support

Winding angle °	Geometric winding deformation %	Pull deformation %	Thermal deformation %	Total deformation %	Feasibility by a conventional superconducting tape	Minimum necessary improvement %	Feasibility by an improved superconducting tape
10	0.3	0,25	<u>3,5</u>	<u>4,05</u>	NO	1,05	YES
25	1.4	0,25	0,93	2,58	YES	-	YES
28,7	1.75	0,25	0	2	YES	-	YES
45	<u>3,4</u>	0,25	-4	(-0,35) <sup>1</sup>	NO	0,4	YES

<sup>1</sup> For a conventional superconducting tape, the mere geometric deformation at room temperature is sufficient to irreversibly damage the tape itself. Therefore, the -0,35 value is significative only for the improved superconducting tape.

Table 2 - Metal support

Winding angle	Geometric winding deformation %	Pull deformation %	Thermal deformation %	Total deformation %	Feasibility by a conventional superconducting tape	Minimum necessary improvement %	Feasibility by an improved superconducting tape
10	0.3	0,25	<u>4</u>	<u>4.55</u>	NO	1.55	YES
25	1.4	0,25	<u>3.5</u>	<u>5.15</u>	NO	2.15	YES
28,7	1.75	0,25	<u>3.3</u>	<u>5.3</u>	NO	2.3	YES
45	<u>3.4</u>	0,25	<u>2.42</u>	<u>6.07</u>	NO	3.07	NO

## CLAIMS

1. A high temperature superconducting cable, comprising a tubular support, a plurality of superconducting tapes including a superconducting material enclosed in a metal covering and spirally wound onto the support so as to form at least an electroinsulated, thermally-insulated and refrigerated superconducting layer, characterised in that the superconducting tapes have a maximum tensile deformation greater than 3%.
- 5 2. The cable according to claim 1, wherein the superconducting tapes comprise at least a metal strip coupled to the metal covering.
- 10 3. The cable according to claim 2, wherein the superconducting tapes comprise two metal strips coupled to the metal covering.
- 15 4. The cable according to claim 2, wherein the metal covering is made of silver or silver-based alloy with magnesium and/or aluminium and/or nickel.
- 5 5. The cable according to claim 2, wherein the metal strip is coupled to the metal covering by welding.
- 20 6. The cable according to claim 2, wherein the metal strip is coupled to the metal covering by brazing.
7. The cable according to claim 2, wherein the metal strip is coupled to the metal covering by gluing.
- 25 8. The cable according to claim 2, wherein the strip is made of non magnetic stainless steel having a low electric conductivity.
9. The cable according to claim 2, wherein the strip is made of bronze.
- 30 10. The cable according to claim 2, wherein the strip is made of aluminium.

11. The cable according to claim 1, wherein the tubular support is made of metal.

12. The cable according to claim 11, wherein the metal tubular support is made of non magnetic stainless steel.

5 13. The cable according to claim 11, wherein the metal tubular support is made of copper.

14. The cable according to claim 11, wherein the metal tubular support has a continuous structure, either smooth or corrugated.

10 15. The cable according to claim 11, wherein the metal tubular support has a spirally wound metal strip structure.

16. The cable according to claim 11, wherein the metal tubular support has a tile structure.

15 17. The cable according to claim 11, wherein the winding angle of the superconducting tapes on the metal tubular support is smaller than 40°.

18. A process for manufacturing high temperature superconducting cables, comprising the steps of:

- providing a tubular support,

20 - enclosing a superconductive material in a metal covering, so as to form superconductive tapes,  
- spirally winding a plurality of superconducting tapes onto the support so as to form at least a superconducting layer,

25 - electroinsulating the superconductive layer,

- thermally insulating the superconductive layer,

- providing the possibility of refrigerating the superconductive layer below a predetermined working temperature, when cables are in use,

30 **characterised by**

- controlling the maximum tensile deformation of the superconducting tapes to have it greater than 3%.

19. Process according to claim 18, comprising the step of:
  - coupling at least a metal strip to the metal covering of the superconducting tapes.
20. Process according to claim 19, comprising the step of:
  - 5 - coupling two metal strips to the metal covering of the superconducting tapes.
21. Process according to claim 19, wherein the coupling step is performed by welding.
22. Process according to claim 19, wherein the coupling step is performed by brazing.
  - 10
23. Process according to claim 19, wherein the coupling step is performed by glueing.
24. Process according to claim 1, wherein the tubular support is made of metal and the winding angle of the superconductive tapes on the metal tubular support is smaller than 40°.
  - 15

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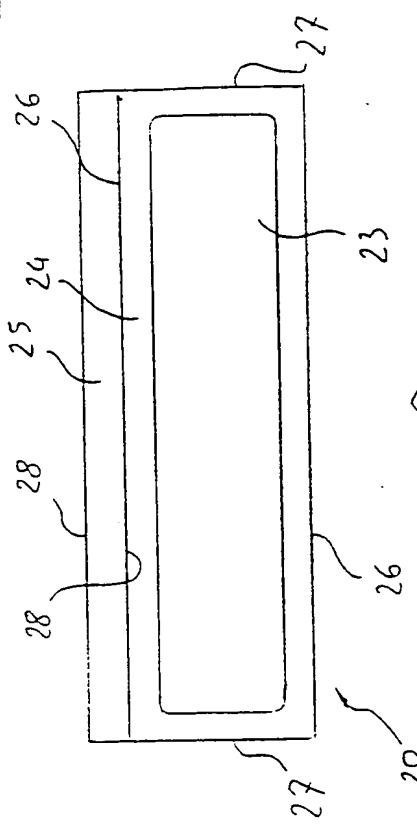
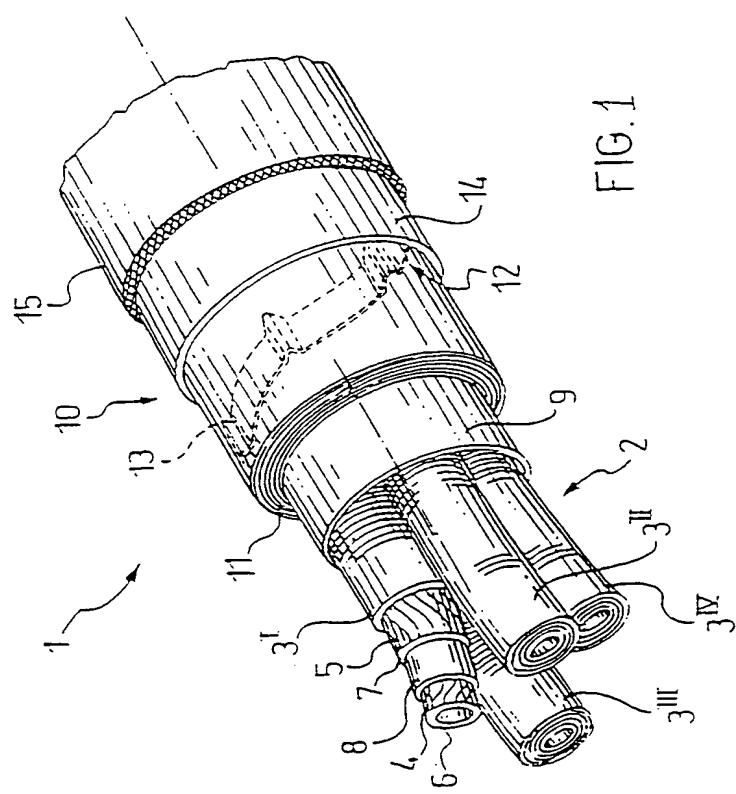
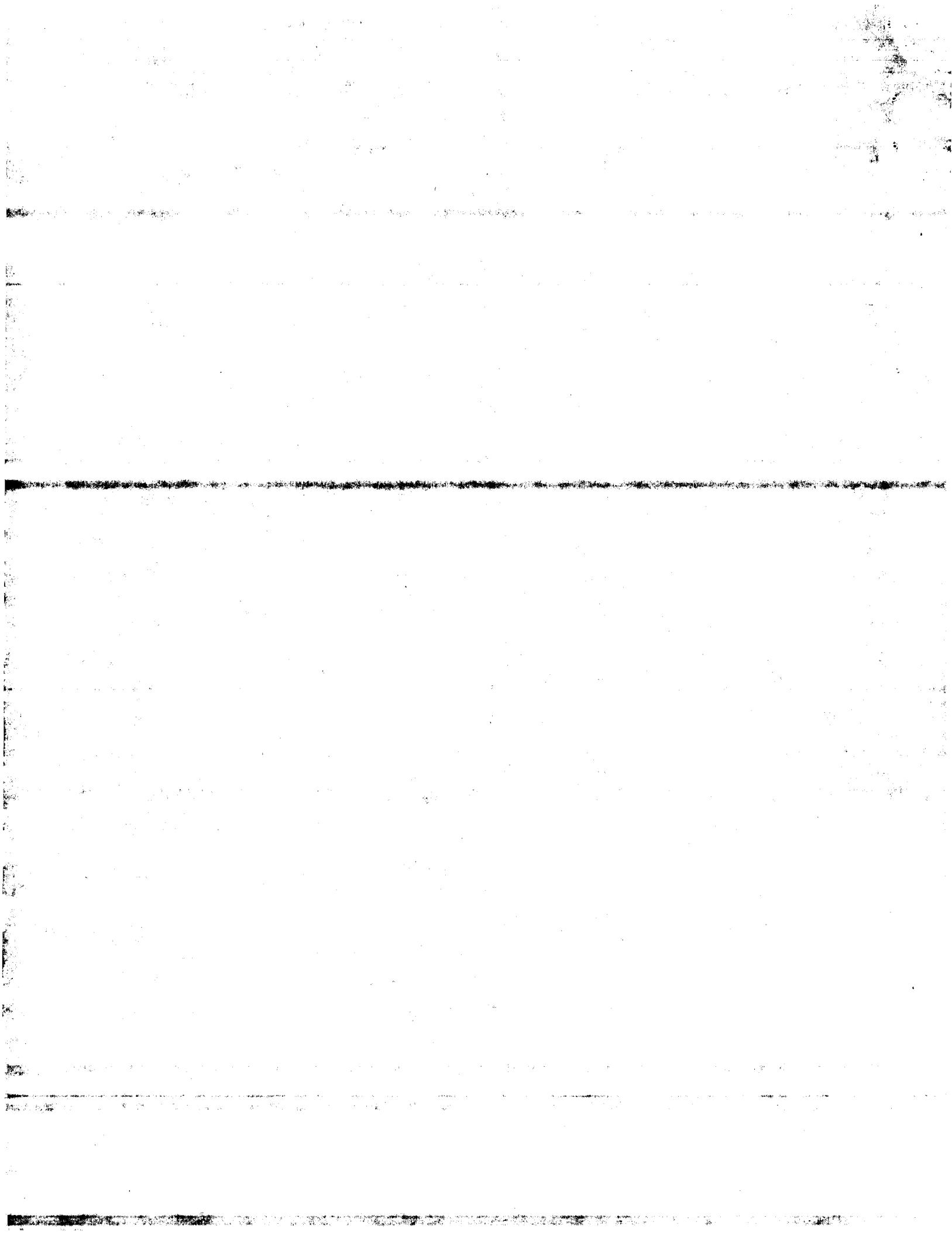


Fig. 2





# INTERNATIONAL SEARCH REPORT

International Application No

PCT/EP 98/04991

**A. CLASSIFICATION OF SUBJECT MATTER**

IPC 6 H01B12/02

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

IPC 6 H01B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

Category	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	EP 0 786 783 A (PIRELLI) 30 July 1997 see page 4, line 24 - page 9, line 44; figures 1-3 -----	1,15,18
A	EP 0 743 658 A (THE BABCOCK & WILCOX COMP.) 20 November 1996 see column 3, line 20 - column 5, line 3; figures 1-3D -----	1-3,5, 10,18-21

Further documents are listed in the continuation of box C.

Patent family members are listed in annex.

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Date of the actual completion of the international search

7 January 1999

Date of mailing of the international search report

14/01/1999

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Information on patent family members

International Application No

PCT/EP 98/04991

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